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FINAL REPORT

(September 1992)

RESEARCH JOINT VENTURE AGREEMENT
No. INT – 91586 – RJVA
BETWEEN
U.S. DEPARTMENT OF AGRICULTURE, FOREST SERVICE, INTERMOUNTAIN RESEARCH STATION
AND
THE UNIVERSITY OF KENTUCKY

Department of Mechanical Engineering
521 CRMS Building
Lexington, Kentucky 40506-0108

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Maximum Spotting Distances in Wind-Driven Crown Fires (SDWCF)

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List of Symbols

English

a	coefficient
A	area of cross-section normal to the trajectory of the fire brand particle
b	coefficient
B	coefficient
C	shape factor
C_D	drag coefficient
d	bulk fuel density
D	diameter of fire brand particle
DTF	dimensionless time of travel in the flame
DTP	dimensionless time of travel in the plume
DTT	dimensionless time of travel in the transition zone
E	net horizontal heat flux
g	acceleration due to gravity
H	average tree height
h_c	heat of combustion
h_i	heat required to ignite fuel
I	fire intensity
k	coefficient
K	von Karman's constant (0.4)
M	$= C\rho_s AD$
$\dot{M}$	fuel consumption rate
q	dynamic pressure
q_f	peak dynamic pressure
q_{max}	maximum dynamic pressure
R	flame spread rate over a continuous fuel bed
r	$= [(b + S/S_f)/a]^{1/2}$
S	flame length coordinate (see Figs. 2 and 3)
S_f	flame length in the S coordinate (see Fig. 3)
S_o	flame-base length in the S coordinate (see Fig. 2)
S(0)	fire brand lofting distance along the S coordinate (see Fig. 2)
SFD	steady flame duration
t	time
TTT	= DTF + DTT + DTP
U	ambient air velocity
U_H	horizontal wind velocity at the height H
U_*	friction velocity
V	velocity
V_o	terminal velocity of fire brand particle defined in Eq. (16)

W weight of fuel consumed/unit area
x horizontal coordinate
X_{max} maximum spotting distance
z vertical coordinate (see Figs. 2 and 3)
z_f vertical flame height (see Fig. 3)
z_o roughness length defined as flame-base height in the z coordinate (see Fig. 2)
$z(0)$ fire brand lofting height along the z coordinate (see Fig. 2)

greeks

β given in Eq. (39)
θ flame tilt angle (see Fig. 2)
ρ density of fire brand particle
ρ_a ambient air density
ρ_p product gas density
ρ_s density of original fire brand particle
τ $= 4C_D V_o(0)/(k\pi g\cos\theta)$
ω gas velocity
ω_f gas velocity at the flame tip

subscripts

tilt tilted column model
vert vertical column model
x x-component
z z-component

1. INTRODUCTION

A mode of fire spread in forests that must be given attention is spotting by fire brands (Williams, 1982; Albini, 1984). The estimation of spotting distances is essential to fire fighting as they generally set the maximum range of fire spread. A model for predicting spot–fire distance from burning trees was proposed by Albini (1979; 1981a; 1981b; 1983).

There are primarily two prominent behaviors in running crown fires; plume–dominated fires and wind–driven fires (Rothermel, 1991, has developed a methodology to predict the behavior and size of crown fires in the northern Rocky mountains). Besides fire spread by continuous torching of tree crowns a potential spread mechanism is by fire brand transport. In the case of plume–dominated fires, where the convection currents are vertical (Rothermel, 1991) estimation of spotting distances may be made by the direct application of Albini's model (Albini, 1979) for spot fire distance from burning trees.

This is so because the basic fluid dynamics are similar and the resulting governing fire brand transport in the flame and the plume are same. In the case of wind–driven fires the structures of both the flame and the plume are affected in many ways, but the most obvious being that the flame and the plume are tilted, and the angle of tilt is dependent on the ambient wind speed and the strength of the fire.

Here a model is developed to predict spotting distances

from wind–driven crown fires. The method of approach is to develop a model that is parallel to the model developed by Albini (1979). A flow chart describing our approach taken to develop the model is shown in Fig. 1.

In an actual forest fire the parameters that can be measured with relative ease and accuracy are: **the flame height, ambient wind velocity, the angle of inclination and the fire depth**. Therefore, advantage of these parameters will be taken to develop the spotting distance model.

2. DEVELOPMENT OF SPOTTING DISTANCE MODEL

A schematic describing the physical situation, the various parameters used, and coordinate system used are shown in Figs. 2 and 3. To simplify the problem without losing the essence of physics governing crown fires, the following assumptions are introduced in addition to the assumptions made by Albini (1979).

(1) The flame and the plume are tilted by the same angle of inclination.

(2) The flame and the plume are idealized as a single line.

2.1 Flame Spread Rate

Using a dimensional analysis, Carrier et al. (1991) have shown that the flame spread rate, R, over a continuous fuel bed is a function of the ambient wind speed, U, and the fuel density, m (fuel mass/area). For convective–diffusive

preheating of the fuel bed,

$$R \simeq (U/m)^{1/2} \tag{1}$$

and for radiative heating of the fuel bed,

$$R \simeq (U/m)^{3/2} \tag{2}$$

For the case of crown fires, Van Wagner (1977) has proposed a more general relationship:

$$R = E/dh_i \tag{3}$$

where E is the net horizontal heat flux, d is the bulk fuel density and h_i is the heat required to ignite the fuel.

2.2 Fire Line Intensity

This is an important parameter that determines the strength of a fire. It is given by the relation,

$$I = h_c WR \tag{4}$$

where h_c is the heat of combustion, and W is the weight of the fuel consumed/unit area.

2.3 Flame Length

Applying Froude (Fr) number scaling law (Emori and Saito, 1983; Jolly and Saito 1992; Hirano and Saito 1992), the relationship between flame length, S_f, (defined in Fig. 3) and fire intensity, I, can be correlated with a simple power law as shown in Eq.(5),

$$S_f \sim (I)^{2/3} \tag{5}$$

Thomas (1963) proved that this power law sustains for relatively small-scale two-dimensional turbulent fires and experimentally determined the constant to be 0.2:

$$S_f = 0.2\ (I)^{2/3} \tag{6}$$

Fons et al. (1963) came up with the same power law correlation as Thomas's equation but with different constant for laboratory scale crib fires,

$$S_f = 0.74\ (I)^{2/3} \tag{7}$$

2.4 Flame Height and Flame Tilt Angle

In wind-driven fires the flame length in the S coordinate, S_f, and the vertical flame height, z_f, are related by the tilt angle, θ, as $z_f/S_f = \cos\theta$, as can be seen in Fig. 3.

In wind-driven fires the flame tilt angle, θ, depends on

the ambient–wind conditions and the fire intensity. Therefore, the flame and plume tilt angle can be correlated with a specific Fr number which restricts the interaction of inertia force of wind (horizontal component of velocity) and of buoyancy force generated by the fire (vertical component of velocity).

For flame tilt angle, θ, an expression obtained by Albini (1981b) from a numerical analysis of wind–driven equations can be applied.

$$\tan\theta = 1.225(U_H^2/gz_f)^{1/2} \qquad (8)$$

the symbols are listed in the list of symbol section. It is assumed that the flame length does not significantly change under wind–aided conditions as tested for laboratory scale pool fires by Emori and Saito (1983). Therefore, the height of the vertical column flame, z_f, and the flame length, S_f in the tilted coordinates remain same. The coordinate for the tilted flame, S, and the vertical column flame can be related through $z/S = \cos\theta$.

2.5 Development of Equations Based on Albini's Model For Wind–Driven Fires

Albini's model which is simple yet holds practical usefulness classifies the flame/plume structure into three zones: (1) flame zone; (2) transition zone; and (3) plume zone.

The first and the third zones are obvious. The transition zone occurs at the end of the flame tip where the gas velocity at the flame tip is sustained up to an additional 60% of the flame length. Its existence was demonstrated by Albini (1979) in his model from an estimate of the dynamic pressure in the flame and the plume.

Modification was made to Albini's model which forms a "right-angle cone" over the fire source (Albini, 1979) by implementing a "tilted-cone structure" to account for the ambient wind (Fig. 3). A comparison of the expressions for the two cases (vertical column fire and tilted fire) are presented in Table I. The quantities that are important for fire-brand lofting, burning, trajectory and maximum spotting distance in wind-driven fires appear in the following section.

2.6 Gas Velocity and Flame Length for Tilted Flames

Consider the tilted cone model shown in Fig. 3. Starting with the conservation equations of mass and momentum and using Albini's assumptions, the gas velocity, ω, can be written as,

$$\omega = 0.408[2g(\cos\theta)(\rho_a/\rho_p - 1)S]^{1/2} \qquad (9)$$

where the symbols used are explained in the list of symbol section and the quantity $\rho_a/\rho_p \simeq 8/3$ for natural fires. Then, the velocity at the flame tip, ω_f [m/s] can be written as below,

$$\omega_f = 2.3[(\cos\theta)S_f]^{1/2} \tag{10}$$

where S_f is defined as,

$$S_f = 10.4\ [\dot{M}/(\cos\theta)^{1/2}]^{2/5} \tag{11}$$

and $\dot{M}$ is the fuel consumption rate. S_f can be measured directly under some realistic situations, so that the following equation can be determined

$$\omega/\omega_f = (S/S_f)^{1/2} \tag{12}$$

2.7 Dynamic Pressure (q) Relationships for Tilted Flames

For the tilted-cone model, the peak dynamic pressure, q_f, occurs at the flame tip. The dynamic pressure at the flame tip for the tilted flame can be described as,

$$q_f = \tfrac{1}{6}\rho_a g S_f \cos\theta(1-\rho_p/\rho_a) \tag{13}$$

The dynamic-pressure decay may be given as,

$$q/q_f = (8/3)[1-(5/8)(S_f/S)^{5/3}](S_f/S)^{2/3} \tag{14}$$

Equation (14) exhibits a maximum value at $S = 1.6S_f$ where $q_{max} = 1.4q_f$. The region beyond the flame tip where the

dynamic pressure increases to its maximum value is the transition region and the velocity of the gas in this region is equal to ω_f.

2.8 Lofting of Fire-brands in Tilted Flames

The motion of an inert cylindrical particle through the three zones may be described as,

$$dS/dt = \omega - V_o \tag{15}$$

The terminal velocity of the particle, V_o is given by

$$V_o = [2mg(\cos\theta/\rho C_D A)]^{1/2} \tag{16}$$

where ρ is the density of the particle, C_D is the drag coefficient (C_D = 1.2 for a cylinder) and A is the area of cross-section normal to the trajectory of the particle. Equation (15) can be integrated to obtain the time of travel by the particle in the three zones. The results of integration are presented for three different zones as a dimensionless time of flight, $\omega t/2S$.

For the flame zone,

$$DTF = 1 - [S_o/S_f]^{1/2} + B[D/S_f]^{1/2} \ln\left[\frac{1 - B[D/S_f]^{1/2}}{[S_o/S_f]^{1/2} - B[D/S_f]^{1/2}}\right] \quad (17)$$

For the transition zone,

$$DTT = 0.2 + B[D/S_f]^{1/2}\left[1 + B(D/S_f)^{1/2} \ln\left[1 + 1/[1 - B(D/S_f)^{1/2}]\right]\right] \quad (18)$$

For the buoyant plume,

$$DFP = \frac{a}{(0.8V_o/\omega_f)^3}\left[\ln\left[\frac{1 - 0.8B[D/S_f]^{1/2}}{1 - 0.8rB[D/S_f]^{1/2}}\right] - [0.8B(D/S_f)^{1/2}](r-1) - 1/2[0.8B(D/S_f)^{1/2}]^2(r^2-1)\right] \quad (19)$$

where, $a = 5.963$, $b = 4.563$, $B \simeq 24$, $S_o = z_o/\cos\theta$ is the flame-base height in the S coordinate (see Fig. 2), S_f is the flame length in the S coordinate (see Fig. 3), and $r = [(b + S_o/S_f)/a]^{1/2}$.

From Eqs. (17), (18) and (19), the time of flight of a fire-brand and the distance along the S coordinate to which it is lofted, S(0), in the three zones can be determined. This means that once S(0) is estimated, the fire brand trajectory

can be determined. It is reasonable to assume that the burning of the fire-brand in the three zones is negligible due to relatively short residence time and that the fire brand is consumed mostly while it is being transported by the ambient wind.

For the purpose of estimating the lofting distance, the total dimensionless time of travel (TTT) which is a sum of the dimensionless time of travel in the flame (DTF), the dimensionless time of travel in the transition zone (DTT) and the dimensionless time of travel in the plume (DTP) are to be used: TTT = DTF + DTT + DTP. The steady flame duration, SFD, described by Albini is equated to TTT in order to determine the lofting distance of the firebrand.

2.9 Burning Rate of Fire Brand

Assuming that the rate of mass loss is proportional to the rate of air supplied to the fuel surface, the following relationships can be obtained.

$$dM/dt = - k\rho_a AU \tag{20}$$

$$M = C\rho_s AD \tag{21}$$

where, C is a constant fixed by the shape of the fire brand, k = 0.0064, ρ_a is density of ambient gas, ρ_s is the density of the original fire brand, A is the cross-section of the fire brand normal to the direction of motion, D is the diameter of

fire brand, and U is assumed constant only for the purpose of evaluating the burning rate of the fire brand.

2.10 Fire Brand Trajectories in Tilted Flames

Once the fire brand is lofted to a height z(0), it will be carried by the ambient wind. In order to estimate the maximum spotting distance, we consider only those fire brands that are completely consumed when they hit the ground (D=0 at z=0).

The equations of motion are:

$$\frac{dx}{dt} = U(x,z) + \omega_x \tag{22}$$

$$\frac{dz}{dt} = \omega_z - V_o(t) \tag{23}$$

Where ω_x is the horizontal component of ω, and ω_z is the vertical component of ω. If the horizontal transport of the fire brand due to the ambient wind begins only after the flame/plume structure disappears, then $\omega_z = 0$, in the equations of motion for the fire brand (Eq. 23). A logarithmic approximation is used for the ambient wind profile, with U as a function of the vertical distance z only.

$$U = [U_*/K] \ln[z/z_o] \tag{24}$$

where, U_*= friction velocity, z_o = roughness length, K = von

Karman's constant ($\simeq 0.4$).

The friction length and the wind-velocity are related to the average tree height of the forest (Albini, 1979) and $z_o = 0.1313H$ and $U_* = 0.16U$, where H is the average tree height. Denoting the horizontal wind speed at the height H by U_H, the expression for horizontal wind speed can be rewritten as

$$U = U_H \ln(z/z_o)/\ln(H/z_o). \tag{25}$$

The burning rate equation is,

$$d(\rho_s D)/dt = - k\rho_a V_o \tag{26}$$

Combining Eq. (26) with the expression for the terminal velocity (Eq.16), the following expression can be obtained,

$$dV_o(t)/dt = -k\pi g(\cos\theta)/4C_D \tag{27}$$

Integrating Eq. (27),

$$V(t) \equiv - dz/dt = V_o(0)[1 - k(\pi g\cos\theta)t/4C_D V_o(0)] \tag{28}$$

Equation (28) implies that the particle slows down its relative fall velocity linearly with time. The burning rate expression (Eq. 26) can be rewritten as

$$d(\rho_s D)/dt = -k\rho_a(-dz/dt) \tag{29}$$

Integrating Eq. (29), we can obtain:

$$(\rho_s D)_o/k\rho_a = \Delta z = z(0) - z(t) \tag{30}$$

where the subscript, o, represents the value at the height z(0), the height to which the fire brand is lofted through the three zones. From the expression for the terminal velocity

$$(\rho_s D)_o = [2V_o^2(0)C_D\rho_a]/[\pi g\cos\theta] \tag{31}$$

Therefore,

$$\Delta z = z(0) - z(t) = 0.5V_o(0)[(4V_o(0)C_D)/[k\pi g\cos\theta] \tag{32}$$

Let $\tau = 4C_D V_o(0)/(k\pi g\cos\theta)$. The equations of motion Eqs. (22) and (23) can be rewritten respectively as,

$$dx/dt = U_H \ln(z/z_o)/[\ln(H/z_o)] + \omega\sin\theta \tag{33}$$

$$dz/dt = - V_o(0)(1 - t/\tau) \tag{34}$$

The vertical component of the buoyant velocity, ω_z, ceases to exist once the fire-brand leaves the three zone structure. Therefore, Eq. (34) can be written as

$$dz/dt = - V_0(0)[z/z(0)]^{1/2} \tag{35}$$

Combining Eqs. (33) and (35),

$$dx/dz = \underbrace{U_H \ln(z/z_0)/\ln(H/z_0)\{-V_0(0)^{-1}[z(0)/z]^{1/2}\}}_{\text{I}} + \underbrace{\omega \sin\theta\{-V_0(0)^{-1}[z(0)/z]^{1/2}\}}_{\text{II}} \tag{36}$$

The first expression on the RHS labelled I, represents the contribution of the vertical column to the spotting distance and the expression labelled II represents the contribution from the tilted column. Integrating for the spotting distance from $z = z(0)$ to 0 and $x = 0$ to X_{max},

$$x_{max}/H = \int_{z(0)}^{0} \frac{U_H}{H} \ln(z/z_0)/\ln(H/z_0)\{-V_0(0)^{-1}[z(0)/z]^{1/2}\}dz + \int_{z(0)}^{0} \frac{\omega \sin\theta}{H}\{-V_0(0)^{-1}[z(0)/z]^{1/2}\}dz \tag{37}$$

It is assumed that the fire brand is always lofted into the plume before it is carried away by the ambient wind. Therefore, the expression for the buoyant velocity in the plume is substituted for ω in Eq. (37).

In the plume zone,

$$\omega = \omega_f\{5.963/(4.563 + z/z_f)\}^{1/2} \tag{38}$$

After integration of Eq. (37), the expression becomes

$$X_{max}/H = 21.9\frac{U_H}{H}(H/g)^{1/2}\{0.362 + 0.5[z(0)/H]^{1/2}\ln[z(0)/H]\} + 14(S_f/H)\beta\sin\theta \tag{39}$$

where $\beta = \ln\{2[bz_f z(0) + z(0)^2]^{1/2} + 2z(0) + bz_f\} - \ln[bz_f]$ and $b = 4.563$.

3. METHODOLOGY TO ESTIMATE THE MAXIMUM SPOTTING DISTANCE IN TILTED FLAMES

(1) Estimate the total time of travel by the fire brand particle in the three zones. This can be achieved by adding the time of travel in Eqs. (17)–(19); or it can be directly estimated from observation. Then, S(0) can be obtained from Eqs. 17–19.

(2) Estimate θ and S_f from direct observation; apply the coordinate relationship, $z = S\cos\theta$, together with S (0) found in the above; and calculate $z(0)$. Using these parameters, S_f, z_f, $z(0)$ together with the estimated values of, U_H and H, the maximum spotting distance can be

estimated from Eq. (39).

(3) Monographs can be prepared for the estimation of the maximum spotting distances by plotting X_{max}/H as a function of D/z_f (Fig. 4). For example, in Fig. 4 the spotting distances are shown for a single wind speed (θ=33°) and three different steady flame durations (SFD). Following the same methodology, monographs for other wind-speed conditions (which cause different θ values) can be prepared. However, a suitable value of D/z_f (or D/S_f) must be known in order to estimate the maximum spotting distance.

A sample problem and method of estimation for maximum spotting distance are presented in **Appendix A**.

4. SUMMARY AND CONCLUSIONS

(1) Albini's model (Albini 1979) to predict spotting distances of fire-brands from vertical column fires was extended to wind-aided crown fires. A thorough analysis of Albini's model and the existing literature on forest fire spread revealed that Albini's model to predict spotting distances is definitely the best (and perhaps the only one) since; (a) it is very comprehensive, taking into account all the important physical parameters associated with the phenomena; (b) the assumptions made in order to develop a

tractable model are reasonable and considering the complex nature of the phenomena in a most simple and practical manner. However, it is likely that assumptions do not result in oversimplifications; and (c) the model allows the estimation of spotting distances through the development of easy-to-understand monographs.

(2) In the lines of Albini's model, a model was developed to predict spotting distances in wind-aided crown fires. It was assumed that the effect of the ambient wind was only to tilt the flame and the plume by the same angle of tilt. A methodology to estimate the spotting distances was developed. An example problem was chosen to compare the spotting distances with and without the effect of the ambient wind. It was found that for a tilt angle, θ=33^{o}, corresponding to an ambient wind speed of 8.88 m/s (20 mph), the difference between the two cases is no greater than 15%.

(3) From this study it is clear that Albini's model and the extended model for wind-aided fires developed here to predict spotting distances are sufficient for practical purposes, since; (a) they retain the important physics of the phenomena; and (b) they are never likely to underpredict the maximum spotting distances. Moreover, increasing the complexity of the models will require numerical solutions of the governing equations, and may not be the best practical approach.

5. Future Work

The concept of steady flame duration (SFD) limits the prediction of spotting distance to non–continuous flames (flames can only exist for a certain period of time). However, for running crown fires of a large scale, fire brand may be lofted to a greater height in which case the maximum spotting distance may be greater. If the fire brand remains inert in the three zone structure, then the spotting distance will increase. Contrary, if the fire brand is not inert, then the maximum spotting distance may or may not change. Therefore, it may be necessary to study the effect of continuous fire on the maximum spotting distance. The following are suggested.

(1) Implement the burning rate effect in the three zone structure.

(2) Evaluate the maximum lofting distance, S(0), in the three zone structure.

(3) Evaluate the maximum spotting distance.

(4) Although a rigorous numerical approach may not be practical, analysis of the full governing equations (i.e. with very few or no assumptions) describing the spotting problem is suggested to validate the above models, since either experimental or practical data are not easy to obtain.

6. Acknowledgements

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TABLE I Comparison of Albini's Model and Present Model

VERTICAL-COLUMN MODEL EQUATIONS (ALBINI, 1979)

Flame Length: $S_f = z_f \sim \dot{M}^{2/5}$, where, $\dot{M}$ is the fuel mass burning rate.

Buoyant Velocity in the Flame: $\omega = 0.408[2g\ (\rho_a/\rho_p - 1)S]^{1/2}$

Flame Tip Velocity: $\omega/\omega_f = (S/S_f)^{1/2}$

Dynamic Pressure q: $q_{vert} \sim \omega_{vert}^2$; q_{max} at $S_f = 1.6S_f$; $q_{max} = 1.4q_f$

Fire-brand Trajectory Equation:
$$X_{max}/H = 21.9\frac{U_H}{H}(H/g)^{1/2}\{0.362 + 0.5(z(0)/H)^{1/2}\ln[z(0)/H]\}$$

TILTED-COLUMN MODEL (WIND-AIDED) EQUATIONS (PRESENT)

Flame Length: $S_f = z_f \sim [\dot{M}/\cos\theta^{1/2}]^{2/5}$
where $\theta = \text{Arctan}\{1.225(U_H^2/gz_f)^{1/2}\}$.

Buoyant Velocity in the Flame:
$\omega = 0.408[2g \times \cos\theta\ (\rho_a/\rho_p - 1)S]^{1/2}$

Flame Tip Velocity: $\omega/\omega_f = (S/S_f)^{1/2}$

Dynamic Pressure q: $q_{tilt} \sim \omega_{tilt}^2$; q_{max} at $S_f = 1.6S_f$; $q_{max} = 1.4q_f$

Fire-brand Trajectory Equation:
$$X_{max}/H = 21.9\frac{U_H}{H}(H/g)^{1/2}\{0.362 + 0.5(z(0)/H)^{1/2}\ln[z(0)/H]\} + 14(S_f/H)\beta\sin\theta$$

where $\beta = \ln[2(az_fz(0) + z(0)^2)^{1/2} + 2z(0) + az_f] - \ln[az_f]$, and $a = 4.563$.

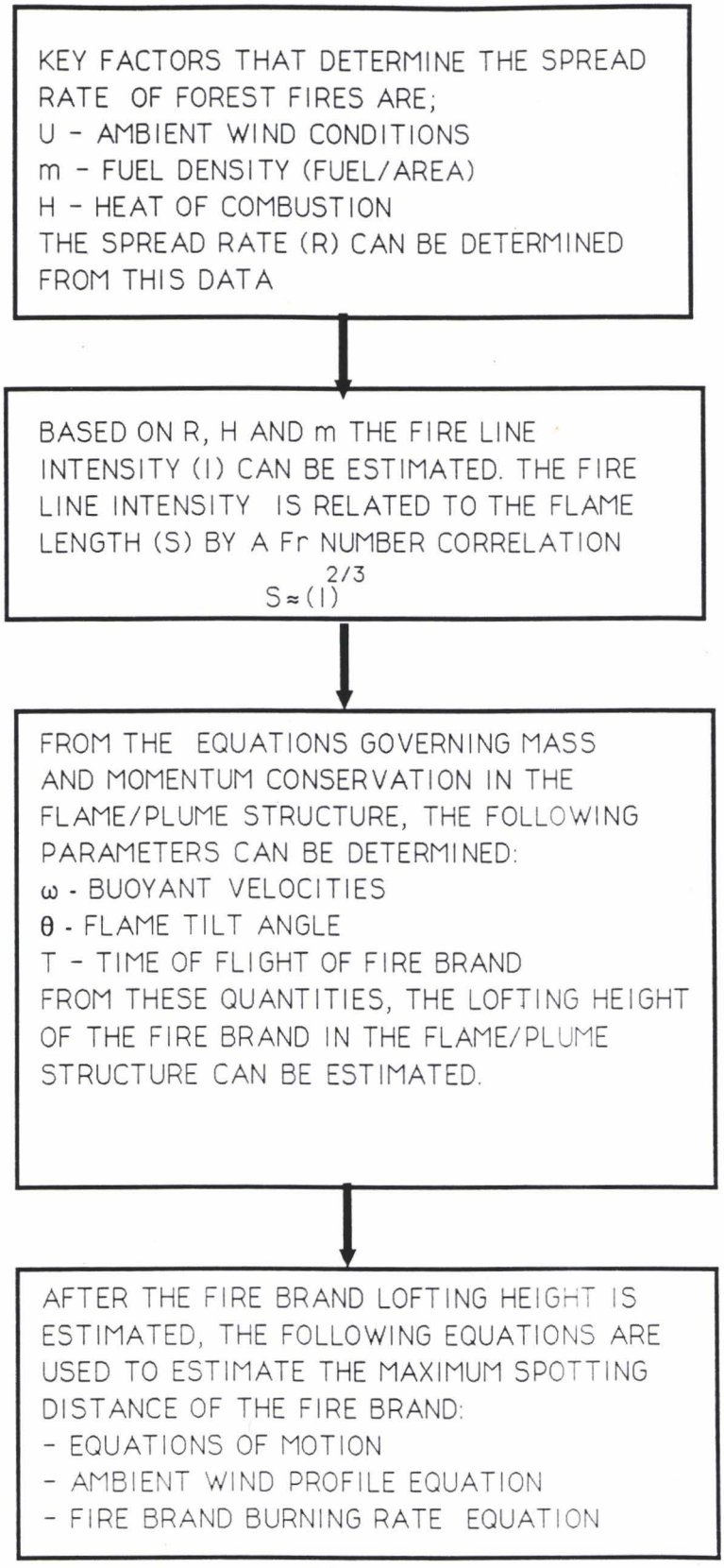
KEY FACTORS THAT DETERMINE THE SPREAD RATE OF FOREST FIRES ARE;
U - AMBIENT WIND CONDITIONS
m - FUEL DENSITY (FUEL/AREA)
H - HEAT OF COMBUSTION
THE SPREAD RATE (R) CAN BE DETERMINED FROM THIS DATA
BASED ON R, H AND m THE FIRE LINE INTENSITY (I) CAN BE ESTIMATED. THE FIRE LINE INTENSITY IS RELATED TO THE FLAME LENGTH (S) BY A Fr NUMBER CORRELATION
$S \approx (I)^{2/3}$
FROM THE EQUATIONS GOVERNING MASS AND MOMENTUM CONSERVATION IN THE FLAME/PLUME STRUCTURE, THE FOLLOWING PARAMETERS CAN BE DETERMINED:
ω - BUOYANT VELOCITIES
θ - FLAME TILT ANGLE
T - TIME OF FLIGHT OF FIRE BRAND
FROM THESE QUANTITIES, THE LOFTING HEIGHT OF THE FIRE BRAND IN THE FLAME/PLUME STRUCTURE CAN BE ESTIMATED.
AFTER THE FIRE BRAND LOFTING HEIGHT IS ESTIMATED, THE FOLLOWING EQUATIONS ARE USED TO ESTIMATE THE MAXIMUM SPOTTING DISTANCE OF THE FIRE BRAND:
- EQUATIONS OF MOTION
- AMBIENT WIND PROFILE EQUATION
- FIRE BRAND BURNING RATE EQUATION

Figure 1 **Flow chart explaining the concept of prediction** model for maximum spotting distance in wind-driven crown fires.

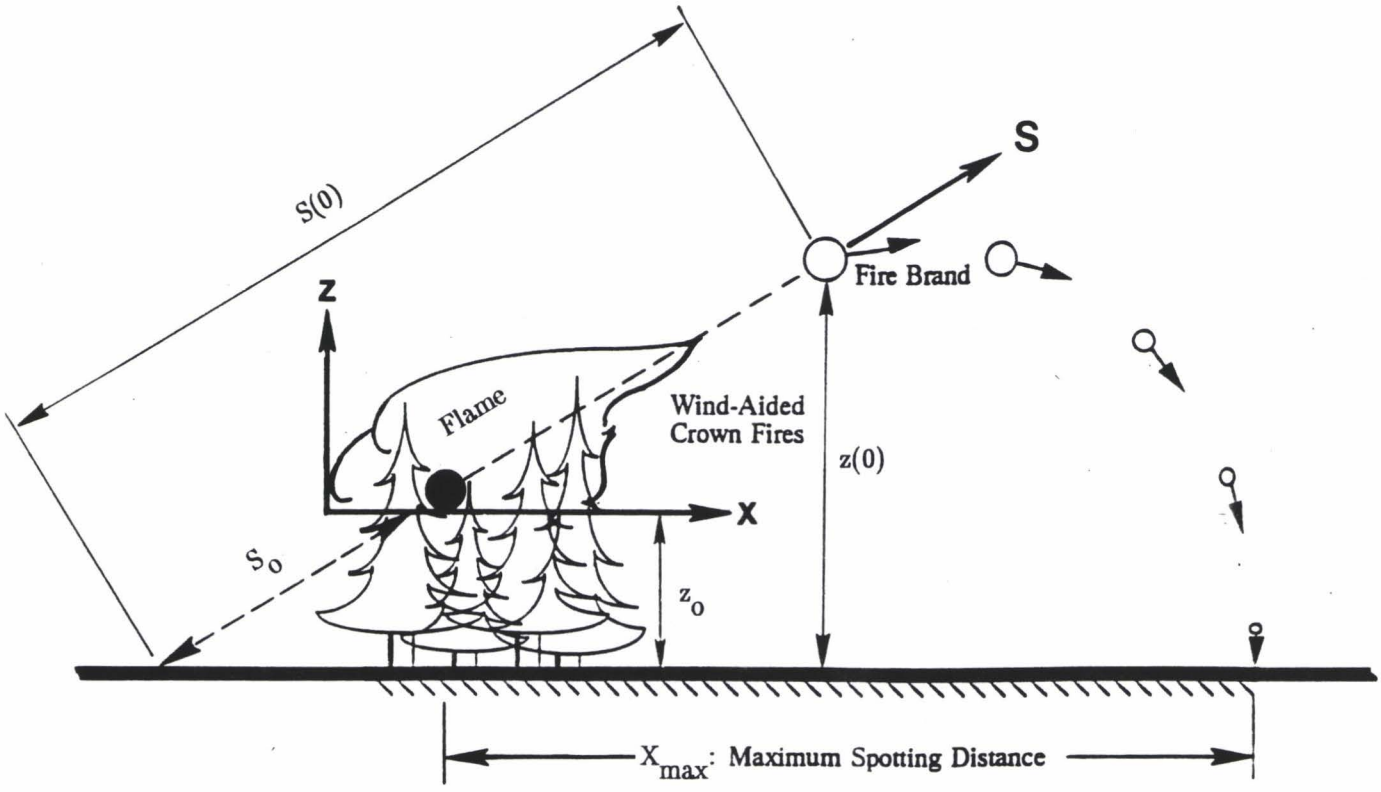

Figure 2 A schematic of fire brand phenomenon (for symbols used, see the list of symbols section in the text).

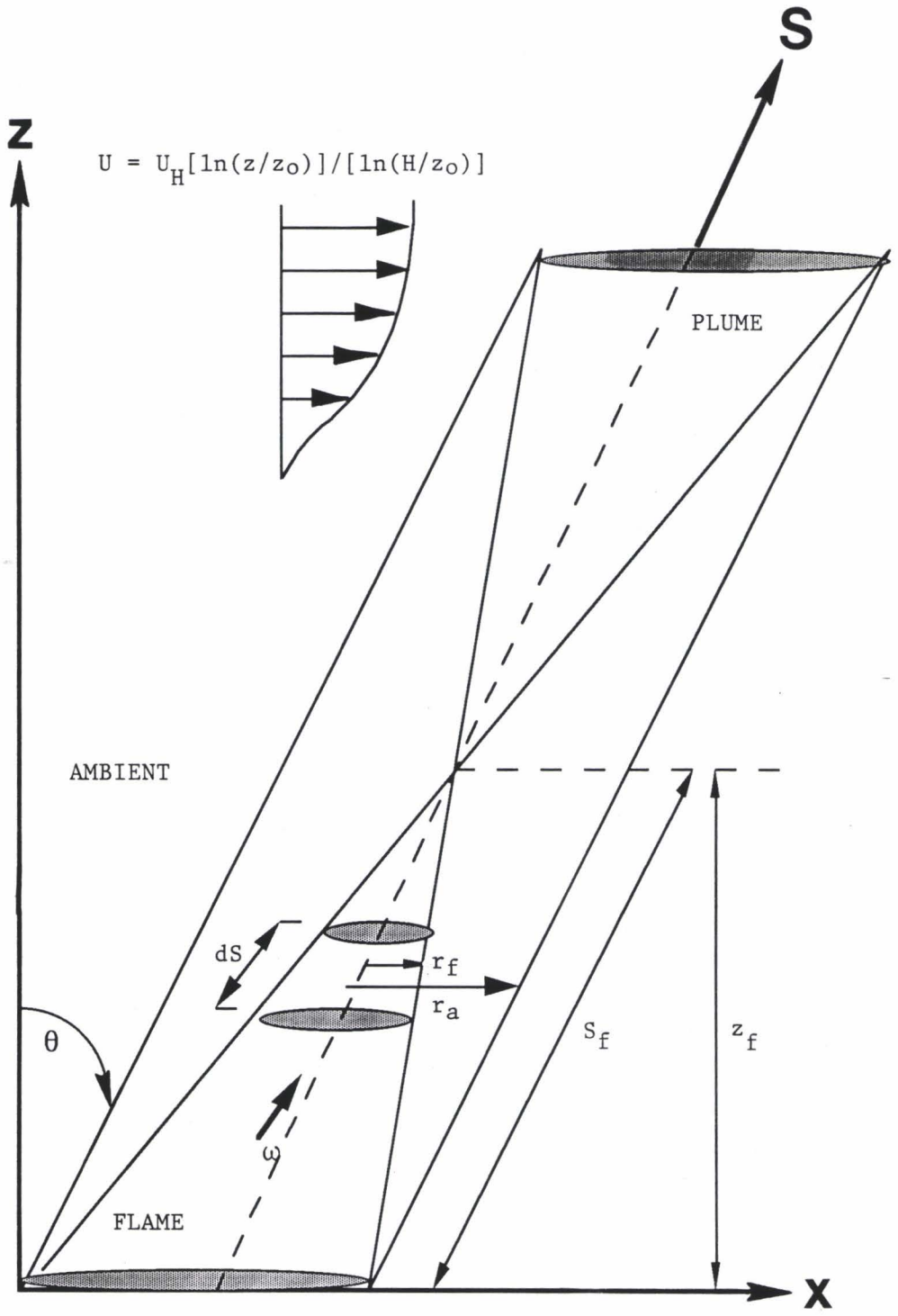

Figure 3 A schematic of conical flame and plume model.

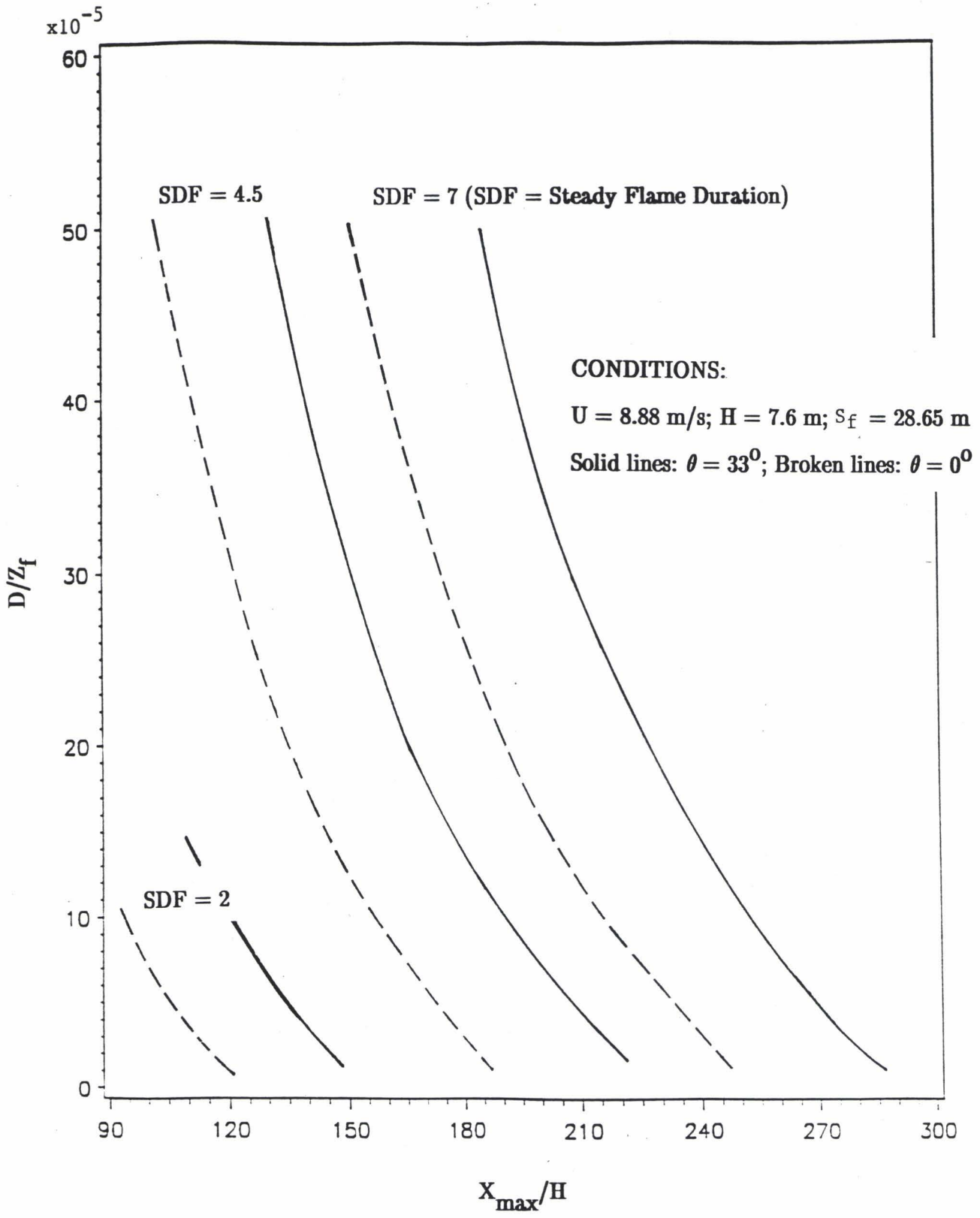

Figure 4 Maximum spotting distance as a function of fire brand diameter for two different tilted flame angles and three different SFD values.

APPENDIX A

To estimate the spotting distances with and without wind effects, an example is chosen from Albini's report, "Spot Fire Distances in Burning Trees – A predictive Model," July 1979, Example 1, p.17 (the copy is attached).

A computer program to calculate the maximum spotting distance for vertical column fires and tilted column (wind-aided) fires is attached. All the calculation processes are documented in the program.

EXAMPLE

INPUT PARAMETERS

* Flame length, S_f = 28.65 m
* Steady flame duration, SFD = 4.5
* Mean wind speed at tree top height, U_H = 8.88 m/s
* Mean tree top height, H = 15.24 m
* $z_o/z_f = S_o/S_f$ = 0.2 (the factors, z_o/z_f, were chosen to match with the example in Albini's report)
* $D/z_f = 0.2 \times 10^{-5}$
* Flame tilt angle, $\theta = \text{Arctan}\{1.225(U_H^2/gz_f)^{1/2}\} = 33^\circ$ measured from observation

STEP I – MAXIMUM SPOTTING DISTANCE EQUATION

In order to estimate the maximum spotting distance, Eq. (39) must be used. It can be seen that all the variables used in Eq. (39) can be obtained from the above input except the fire

brand lofting height z(0). Therefore, we obtain z(0) as in step II.

STEP II – ESTIMATION OF z(0)

Albini Model:

The steady flame duration SFD is equated to the total time of travel (dimensionless) which is found to be,

$$TTT = SFD = DTF + DTT + DTP \qquad (A.1)$$

Use input parameters given in the Albini Report, e.g., TTT = SFD = 4.5, then the figure 7 (Albini Report page 13) gives you approximately z(0) = 200 m for H/z_f = [the burning tree height]/[steady flame height] > 0.5. Or our computer program gives you z(0) = Z0 (in our computer program) = 206.

Present Model:

From Eqs. (17) – (19), the value z(0) = TZ0 (in our computer program) can be calculated using the attached computer program.

Assuming TTT = 4.5,

$$4.5 = DTF + DTT + DTP$$

then, TZ0 (final lofting height in the z coordinate) = 173 m (see the computer program page 6, #28).

STEP III – MAXIMUM SPOTTING DISTANCE

(1) Albini Model ($\theta = 0^{o}$)

From steps I and II using Eq. (39), $X_{max,vert} \simeq 1250$ m

(see the computer program, page 4, #28, second column).

(2) Present Model ($\theta = 33^{o}$)

From steps I and II using Eq. (39), $X_{max,tilt} \simeq 1510$ m

(see the computer program, page 4, #28, first column)

EXAMPLES

Two examples are given to help familiarize the reader with computation procedures. From the statements of the problems one can obtain all the information necessary to complete the worksheets as shown. The reader is encouraged to reconstruct the process to see how each number is used.

Example 1. A recurrent fire control problem on the Coconino National Forest near Flagstaff, Arizona, is spotting when thickets of small Ponderosa pine torch out under strong wind. Estimate maximum spot fire distance if a group of 20 trees, each 6 inches in diameter, torches out when the windspeed is 20 mi/h, measured at the nearest Fire-Danger Rating station (i.e., a 20-foot tower anemometer in a clearing). The trees that torch out are about 50 feet tall; the terrain can be considered flat with broken cover of 50-foot trees.

This problem is shown in the completed worksheet of exhibit 2. Note that in step 5 no windspeed correction for height above terrain was necessary, since the 20-foot tower windspeed is close to the "mean treetop height" (25 feet).

WORKSHEET FOR ESTIMATING MAXIMUM SPOT FIRE DISTANCE

1. Describe trees(s) assumed to torch out.
   Species Ponderosa Pine DBH 6 (cm-(in)) Height 50 (m-(ft)) Number simultaneous 20
   † (use in step 2) † (use in step 4)† (use in step 3, fig 6)†
   See table II for number of figure to use in step 2.

2. The steady flame from one burning tree.
   From fig ((3A)-4A-5A): Flame height 29 (m-(ft)) From fig (3B-4B-5B): Duration 8.2
   From fig 6: Flame height multiplier 3.25. From fig 6: Flame duration multiplier .55

3. Adjusted values: Steady flame height 94 (m-(ft)). Steady flame duration 4.5
   (use in step 4) † (use in step 4, fig 7)†

4. Tree height (step 1) ÷ Adjusted steady flame height (step 3) = .53 (use in fig 7)
   From fig 7: Lofted firebrand height/steady flame height 6.6.
   Multiply by adjusted steady flame height (step 3). Result: 620 (m-(ft))
   Add 1/2 tree height (recorded in step 1). Result: 650 (m-(ft)) (use in step 6, fig 8)

5. Windspeed adjustments. Record for reference:
   At elevation — (m-ft) at height 20 (m-(ft)) windspeed is 20 (km/h-(mi/h))
   Avg. elevation — (m-ft). Mean treetop height along firebrand path 25 (m-(ft))
   Difference = — (m-ft) (use in fig 2) (use in fig 2 and step 6, fig 8)†
   From fig 2: windspeed relative to value at same height but at avg. elevation 1 (X)
   Windspeed reference height ÷ mean treetop height = 0.8 (use in fig 1 if greater than 1)
   See instructions for step 5 (use of fig 1 may not be indicated)
   From fig 1, or by estimate, windspeed at reference height relative to treetop 1 (Y)
   Divide reference windspeed by (X) and result by (Y). Result 20 (km/h-(mi/h))
   (use in fig 8)†

6. From fig 8(A-B): Maximum spot distance over flat terrain .92 (km-(mi))

7. Correct for terrain relief along flight path if necessary. FLAT
   Firebrand source is located nearest to:
   Leeward midslope ____ valley floor ____ windward midslope ____ ridgetop ____
   Use fig no: 9A 9B 9C 9D
   Elevation difference from ridge to valley ____ (m-ft)
   Distance from ridge to valley as would be shown on map ____ (km-mi)
   Spot distance from step 6 ÷ ridge-to-valley distance = ____ (use in fig 9)
   From fig 9(A-B-C-D): Spot distance in sinusoidal terrain/flat terrain distance ____
   Multiply by maximum spot distance over flat terrain (step 6).
   Result: .92 (km-(mi))
   This is the maximum spot distance (as shown on map) estimate†

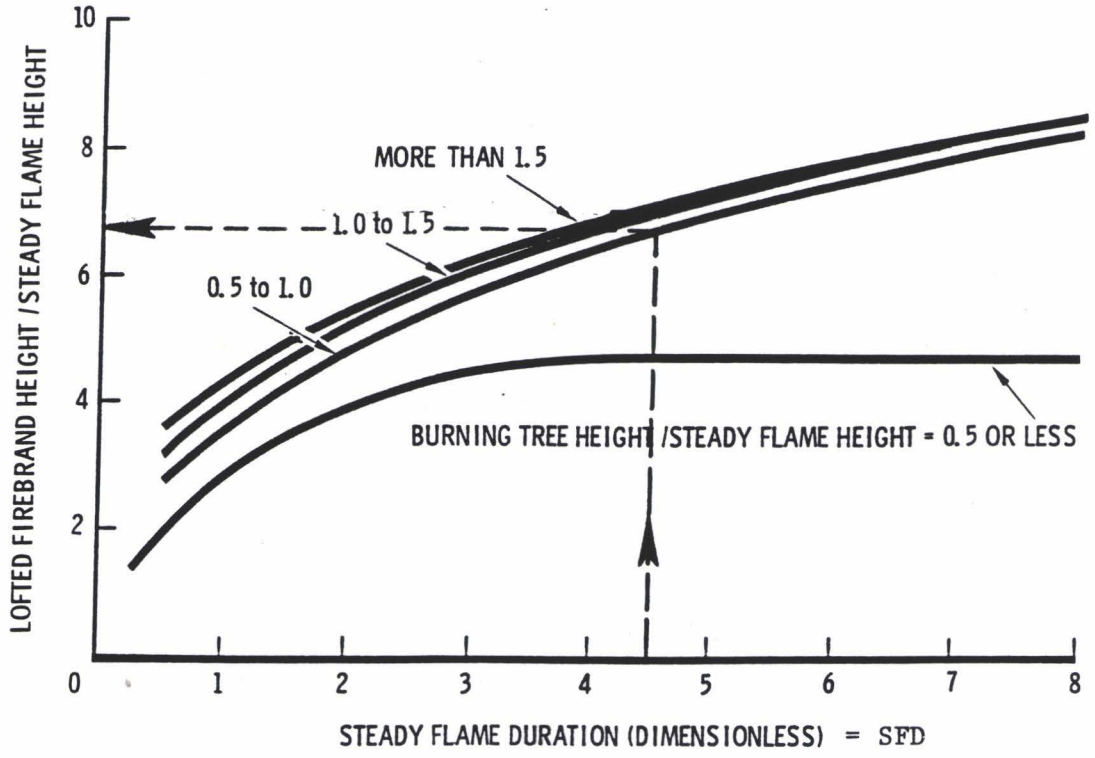

Figure 7.--Height of firebrands lofted by burning trees.

APPENDIX B

COMPUTER PROGRAM (pages 1–3)

and

CALCULATION FOR H = 7.6 m (pages 4–7)
and H = 15.24 m (pages 8–11)

```
C=====================================================================
C     PROGRAM TO CALCULATE  THE MAXIMUM SPOTTING DISTANCE IN VERTICAL
C     COLUMN AND TILTED (WIND-AIDED) FOREST FIRES.
C
C****DEFINITIONS OF VARIOUS PARAMETERS USED IN THE PROGRAM*************
C
C     DPH - LOFTING DISTANCE/FLAME HEIGHT (LENGTH)
C     LOFTING DISTANCE - DISTANCE TRAVELLED BY THE FIREBRAND IN THE
C     FLAME + TRANSITION ZONE + PLUME
C     DTF - DIMENSIONLESS TIME OF TRAVEL IN THE FLAME
C     DTT - DIMENSIONLESS TIME OF TRAVEL IN THE TRANSITION ZONE
C     DTP - DIMENSIONLESS TIME OF TRAVEL IN THE PLUME
C     TTT - TOTAL TIME OF TRAVEL (DIMENSIONLESS) = DTF + DTT + DTP
C     ZO - FINAL LOFTING HEIGHT IN A VERTICAL COLUMN FIRE.
C          IN COMPUTER OUTPUT, ZO IS PRESENTED ONLY FOR COMPARISON
C     XMAX - MAXIMUM SPOTTING DISTANCE FOR A VERTICAL COLUMN FIRE
C     TZO - FINAL LOFTING HEIGHT IN A TILTED COLUMN FIRE
C     TXMAX - MAXIMUM SPOTTING DISTANCE FOR A TILTED COLUMN FIRE
C     XRATIO - XMAX/TXMAX
C     R, TMAX, HMAX - INTERMEDIATE VARIABLES
C     B - CONSTANT (SEE REPORT)
C     A, B1 - CONSTANTS RELATED TO BUOYANT VELOCITY IN THE PLUME
C     THETA - ANGLE OF INCLINATION
C     G - ACCELERATION DUE TO GRAVITY
C     SDZF - STEADY FLAME DURATION/FLAME HEIGHT (LENGTH)
C
C*****INPUT PARAMETERS BASED ON EXAMPLE FROM ALBINI'S REPORT***********
C
C     H - AVERAGE TREE TOP HEIGHT
C     ZF - FLAME HEIGHT (LENGTH)
C     UH - MEAN WIND SPEED
C     ZOZF - BASE OF FLAME HEIGHT/FLAME HEIGHT
C     SP - SPECIFIC GRAVITY OF FIREBRAND
C     DZF - FIREBRAND DIAMETER/FLAME HEIGHT(LENGTH)
C     CD - DRAG COEFFICIENT
C=====================================================================

      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION DPH(100),DTF(100),DTT(100),DTP(100),
     &          TTT(100),ZO(100), XMAX(100), TZO(100),TXMAX(100),
     &          XRATIO(100),R(100)
C
        OPEN (UNIT=5,FILE='/CFIRE RES1', STATUS='UNKNOWN')
        OPEN (UNIT=7,FILE='/CFIRE RES2', STATUS='UNKNOWN')
C
      B=24.27D0
      A=5.963D0
      B1=4.563D0
      PI=4.D0*DATAN(1.D0)
      H=7.60D0
      ZF=28.65D0
      UH=8.888D0
      ZOZF=0.2D0
      SZOZF=DSQRT(ZOZF)
      G=9.81D0
```

```
      SP=300.D0
      CD=1.2D0
      THETA = DATAN(1.225D0*UH/DSQRT(G*ZF))
      ANGLE = THETA*180.D0/PI
      DZF = 0.2D-05


         SDZF = B* DSQRT(DZF)
         WRITE(5,1000)SP,CD,H,UH,ZF,ZOZF,ANGLE,DZF
         WRITE(7,1002)
         WRITE(7,1003)

         DO 101 J = 2,60

C     CALCULATE THE TOTAL TRAVEL TIME WITHIN THE FLAME AND PLUME
            DPH(1) = 1.6D0
            DPH(J) = DPH(J-1) + 0.2D0

            DTF(J) = 1.D0 - SZOZF + SDZF*
     &               DLOG((1.D0-SDZF)/(SZOZF-SDZF))
            DTT(J) = 0.2D0 + SDZF*(1.D0 + SDZF*
     &               DLOG(1.D0 + 1.D0/(1.D0-SDZF)))
            R(J) = ((B1+ DPH(J))/A)**(0.5D0)
            DTP1 = A/((0.8D0*SDZF)**3)
            DTP2N = (1.D0 - 0.8D0*SDZF)
            DTP2D= (1.D0 - 0.8D0*R(J)*SDZF)
            DTP2 = DLOG(DTP2N/DTP2D)
            DTP3 = (0.8D0*SDZF)*(R(J)-1.D0)
            DTP4 = 0.5D0*((0.8D0*SDZF)**2)*(R(J)*R(J) -1)
            DTP(J) = DTP1*(DTP2-DTP3-DTP4)

C*********************************************************************
C           TOTAL TIME OF TRAVEL
            TTT(J) = DTF(J) + DTT(J) + DTP(J)
C*********************************************************************

C     FOR THE CASE OF THE VERTICAL COLUMN FIRE.........

C*********************************************************************
C           MAXIMUM LOFTING DISTANCE
            ZO(J) = DPH(J) * ZF
C*********************************************************************

            XMAX1 = 21.9D0*UH*DSQRT(H/G)

C*********************************************************************
C           MAXIMUM SPOTTING DISTANCE FOR VERTICAL COLUMN FIRE
            XMAX(J) = XMAX1*(0.362D0 +DSQRT(ZO(J)/H)*0.5D0
     &                *DLOG(ZO(J)/H))
C*********************************************************************

C     IF THE FLAME IS TILTED DUE TO EXTERNAL WIND.......

            TZO(J) = ZO(J)*DCOS(THETA)
            A1 = 4.563D0*ZF
```

```
            BETA1 = 2.D0*DSQRT(A1*TZO(J) +TZO(J)*TZO(J))
            BETA2 = 2.D0*TZO(J) + A1 + BETA1
            BETA3 = DLOG(BETA2)
            BETA = BETA3 - LOG(A1)
            TXMAX1 = (14.D0*ZF*DSIN(THETA)*BETA)/H
            TXMAX2 = 21.9D0*UH*DSQRT(H/G)
            TXMAX3 = (0.362D0+DSQRT(TZO(J)/H)*0.5D0*DLOG(TZO(J)/H))
C
C*********************************************************************
C   MAXIMUM SPOTTING DISTANCE FOR A TILTED FLAME
            TXMAX(J) = H*TXMAX1 + TXMAX2*TXMAX3
C*********************************************************************

            XRATIO(J) = XMAX(J)/TXMAX(J)
            WRITE(5,1001)J-1,TXMAX(J),XMAX(J),XRATIO(J),BETA
            WRITE(7,1001)J-1,TZO(J),ZO(J),TTT(J),BETA
101       CONTINUE


1000  FORMAT('CALCULATION AND COMPARISON OF MAXIMUM SPOTTING',/,
     & 'DISTANCES IN VERTICAL COLUMN AND TILTED FIRES',///,2X,
     & 'DEFINITIONS AND CONDITIONS USED FOR CALCULATIONS', //, 2X,
     & 'SPECIFIC GRAVITY OF FIREBRANDS, M  = ',E9.4,/,2X,
     & 'DRAG COEFFICIENT OF FIREBRANDS IN M = ',E9.4,/,2X,
     & 'AVERAGE HEIGHT OF TREE-LINE H IN M  = ',E9.4,/,2X,
     & 'WIND-SPEED AT TREE HEIGHT UH IN M/S = ',E9.4,/,2X,
     & 'FLAME HEIGHT ZF IN M = ',E9.4,/,2X,
     & 'RATIO OF BASE OF FLAME HEIGHT TO FLAME HEIGHT = ', E9.4,/,2X,
     & 'THE ANGLE OF INCLINATION THETA IN DEG = ',F6.2,/,2X,
     & 'PARTICLE DIAMETER TO  FLAME HEIGHT RATIO = ',E9.4,/,2X,
     & 'XRATIO -- VERTICAL/TILTED MAXIMUM SPOTTING DISTANCES',///,
     &'           --SPOTTING DISTANCE IN M-- ',//,
     &6X,'WIND-AIDED',5X,'STILL-AIR',7X,'XRATIO',7X,' BETA',/)
1001  FORMAT(1X,I3,4(2X,D12.6))
1002  FORMAT(2X,
     & 'TZO -- FINAL LOFTING HEIGHT IN A TILTED COLUMN FIRE',/,
     & 2X,'       ****FOR TZO, SEE FIGURE 2****',/,
     & 2X,'Z0  -- FINAL LOFTING HEIGHT IN A VERTICAL COLUMN FIRE',/,
     & 2X,'       ****ZO PRESENTED ONLY FOR COMPARISON****',/,
     & 2X,'TTT -- TOTAL TIME OF TRAVEL (DIMENSIONLESS)',
     &    ' = DTF + DTT + DT ',/,
     & 2X,'BETA-- PARAMETER IN THE FIRE BRAND TRAJECTORY',/,
     & 9X,'EQUATION FOR TILTED FLAMES',/,
     & 9X,'(SEE REPORT EQUATION 39)',//)
1003  FORMAT(10X,'TZO',11X,'ZO',12X,'TTT',11X,'BETA',/)

      END
```

CALCULATION AND COMPARISON OF MAXIMUM SPOTTING
DISTANCES IN VERTICAL COLUMN AND TILTED FIRES

DEFINITIONS AND CONDITIONS USED FOR CALCULATIONS

SPECIFIC GRAVITY OF FIREBRANDS, M = .3000E+03
DRAG COEFFICIENT OF FIREBRANDS IN M = .1200E+01
AVERAGE HEIGHT OF TREE-LINE H IN M = .7600E+01
WIND-SPEED AT TREE HEIGHT UH IN M/S = .8888E+01
FLAME HEIGHT ZF IN M = .2865E+02
RATIO OF BASE OF FLAME HEIGHT TO FLAME HEIGHT = .2000E+00
THE ANGLE OF INCLINATION THETA IN DEG = 33.00
PARTICLE DIAMETER TO FLAME HEIGHT RATIO = .2000E-05
XRATIO -- VERTICAL/TILTED MAXIMUM SPOTTING DISTANCES

--SPOTTING DISTANCE IN M--

	WIND-AIDED	STILL-AIR	XRATIO	BETA
1	0.656536D+03	0.489291D+03	0.745262D+00	0.109485D+01
2	0.710156D+03	0.537185D+03	0.756433D+00	0.114842D+01
3	0.762061D+03	0.583890D+03	0.766199D+00	0.119870D+01
4	0.812434D+03	0.629515D+03	0.774851D+00	0.124612D+01
5	0.861427D+03	0.674154D+03	0.782601D+00	0.129101D+01
6	0.909166D+03	0.717886D+03	0.789609D+00	0.133368D+01
7	0.955760D+03	0.760781D+03	0.795996D+00	0.137436D+01
8	0.100130D+04	0.802899D+03	0.801855D+00	0.141323D+01
9	0.104587D+04	0.844293D+03	0.807263D+00	0.145048D+01
10	0.108954D+04	0.885010D+03	0.812280D+00	0.148624D+01
11	0.113236D+04	0.925091D+03	0.816956D+00	0.152063D+01
12	0.117440D+04	0.964575D+03	0.821331D+00	0.155377D+01
13	0.121571D+04	0.100349D+04	0.825439D+00	0.158575D+01
14	0.125632D+04	0.104188D+04	0.829309D+00	0.161666D+01
15	0.129628D+04	0.107976D+04	0.832967D+00	0.164656D+01
16	0.133562D+04	0.111716D+04	0.836432D+00	0.167554D+01
17	0.137438D+04	0.115409D+04	0.839722D+00	0.170363D+01
18	0.141258D+04	0.119060D+04	0.842854D+00	0.173091D+01
19	0.145025D+04	0.122668D+04	0.845841D+00	0.175742D+01
20	0.148742D+04	0.126237D+04	0.848695D+00	0.178321D+01
21	0.152411D+04	0.129767D+04	0.851427D+00	0.180831D+01
22	0.156034D+04	0.133261D+04	0.854047D+00	0.183276D+01
23	0.159614D+04	0.136719D+04	0.856561D+00	0.185660D+01
24	0.163151D+04	0.140143D+04	0.858979D+00	0.187985D+01
25	0.166648D+04	0.143535D+04	0.861307D+00	0.190255D+01
26	0.170106D+04	0.146895D+04	0.863550D+00	0.192473D+01
27	0.173526D+04	0.150224D+04	0.865715D+00	0.194641D+01
28	0.176911D+04	0.153524D+04	0.867807D+00	0.196760D+01
29	0.180261D+04	0.156796D+04	0.869829D+00	0.198834D+01
30	0.183578D+04	0.160041D+04	0.871786D+00	0.200864D+01
31	0.186862D+04	0.163258D+04	0.873682D+00	0.202853D+01
32	0.190115D+04	0.166450D+04	0.875521D+00	0.204801D+01
33	0.193339D+04	0.169617D+04	0.877304D+00	0.206711D+01
34	0.196532D+04	0.172759D+04	0.879036D+00	0.208583D+01
35	0.199698D+04	0.175878D+04	0.880720D+00	0.210421D+01

36	0.202836D+04	0.178974D+04	0.882356D+00	0.212224D+01
37	0.205948D+04	0.182048D+04	0.883949D+00	0.213994D+01
38	0.209034D+04	0.185099D+04	0.885500D+00	0.215733D+01
39	0.212095D+04	0.188130D+04	0.887010D+00	0.217441D+01
40	0.215131D+04	0.191140D+04	0.888483D+00	0.219120D+01
41	0.218144D+04	0.194130D+04	0.889919D+00	0.220770D+01
42	0.221134D+04	0.197101D+04	0.891321D+00	0.222393D+01
43	0.224101D+04	0.200052D+04	0.892689D+00	0.223990D+01
44	0.227046D+04	0.202985D+04	0.894025D+00	0.225560D+01
45	0.229970D+04	0.205900D+04	0.895331D+00	0.227106D+01
46	0.232874D+04	0.208797D+04	0.896608D+00	0.228628D+01
47	0.235757D+04	0.211676D+04	0.897857D+00	0.230127D+01
48	0.238620D+04	0.214538D+04	0.899078D+00	0.231603D+01
49	0.241465D+04	0.217384D+04	0.900274D+00	0.233057D+01
50	0.244290D+04	0.220214D+04	0.901445D+00	0.234490D+01
51	0.247097D+04	0.223028D+04	0.902592D+00	0.235902D+01
52	0.249886D+04	0.225826D+04	0.903716D+00	0.237295D+01
53	0.252657D+04	0.228609D+04	0.904818D+00	0.238667D+01
54	0.255411D+04	0.231377D+04	0.905898D+00	0.240021D+01
55	0.258149D+04	0.234130D+04	0.906957D+00	0.241357D+01
56	0.260870D+04	0.236869D+04	0.907997D+00	0.242675D+01
57	0.263574D+04	0.239594D+04	0.909017D+00	0.243975D+01
58	0.266263D+04	0.242305D+04	0.910019D+00	0.245258D+01
59	0.268937D+04	0.245002D+04	0.911002D+00	0.246525D+01

TZO -- FINAL LOFTING HEIGHT IN A TILTED COLUMN FIRE
****FOR TZO, SEE FIGURE 2****
ZO -- FINAL LOFTING HEIGHT IN A VERTICAL COLUMN FIRE
****ZO PRESENTED ONLY FOR COMPARISON****
TTT -- TOTAL TIME OF TRAVEL (DIMENSIONLESS) = DTF + DTT + DT
BETA-- PARAMETER IN THE FIRE BRAND TRAJECTORY
EQUATION FOR TILTED FLAMES
(SEE REPORT EQUATION 39)

	TZO	ZO	TTT	BETA
1	0.432495D+02	0.515700D+02	0.102627D+01	0.109485D+01
2	0.480550D+02	0.573000D+02	0.113344D+01	0.114842D+01
3	0.528605D+02	0.630300D+02	0.124230D+01	0.119870D+01
4	0.576660D+02	0.687600D+02	0.135284D+01	0.124612D+01
5	0.624715D+02	0.744900D+02	0.146502D+01	0.129101D+01
6	0.672770D+02	0.802200D+02	0.157884D+01	0.133368D+01
7	0.720825D+02	0.859500D+02	0.169425D+01	0.137436D+01
8	0.768880D+02	0.916800D+02	0.181126D+01	0.141323D+01
9	0.816935D+02	0.974100D+02	0.192983D+01	0.145048D+01
10	0.864989D+02	0.103140D+03	0.204994D+01	0.148624D+01
11	0.913044D+02	0.108870D+03	0.217159D+01	0.152063D+01
12	0.961099D+02	0.114600D+03	0.229475D+01	0.155377D+01
13	0.100915D+03	0.120330D+03	0.241941D+01	0.158575D+01
14	0.105721D+03	0.126060D+03	0.254554D+01	0.161666D+01
15	0.110526D+03	0.131790D+03	0.267315D+01	0.164656D+01
16	0.115332D+03	0.137520D+03	0.280220D+01	0.167554D+01
17	0.120137D+03	0.143250D+03	0.293269D+01	0.170363D+01
18	0.124943D+03	0.148980D+03	0.306459D+01	0.173091D+01
19	0.129748D+03	0.154710D+03	0.319791D+01	0.175742D+01
20	0.134554D+03	0.160440D+03	0.333262D+01	0.178321D+01
21	0.139359D+03	0.166170D+03	0.346872D+01	0.180831D+01
22	0.144165D+03	0.171900D+03	0.360618D+01	0.183276D+01
23	0.148970D+03	0.177630D+03	0.374500D+01	0.185660D+01
24	0.153776D+03	0.183360D+03	0.388516D+01	0.187985D+01
25	0.158581D+03	0.189090D+03	0.402666D+01	0.190255D+01
26	0.163387D+03	0.194820D+03	0.416949D+01	0.192473D+01
27	0.168192D+03	0.200550D+03	0.431362D+01	0.194641D+01
28	0.172998D+03	0.206280D+03	0.445906D+01	0.196760D+01
29	0.177803D+03	0.212010D+03	0.460579D+01	0.198834D+01
30	0.182609D+03	0.217740D+03	0.475380D+01	0.200864D+01
31	0.187414D+03	0.223470D+03	0.490309D+01	0.202853D+01
32	0.192220D+03	0.229200D+03	0.505363D+01	0.204801D+01
33	0.197025D+03	0.234930D+03	0.520543D+01	0.206711D+01
34	0.201831D+03	0.240660D+03	0.535848D+01	0.208583D+01
35	0.206636D+03	0.246390D+03	0.551275D+01	0.210421D+01
36	0.211442D+03	0.252120D+03	0.566826D+01	0.212224D+01
37	0.216247D+03	0.257850D+03	0.582498D+01	0.213994D+01
38	0.221053D+03	0.263580D+03	0.598292D+01	0.215733D+01
39	0.225858D+03	0.269310D+03	0.614206D+01	0.217441D+01
40	0.230664D+03	0.275040D+03	0.630239D+01	0.219120D+01
41	0.235469D+03	0.280770D+03	0.646390D+01	0.220770D+01
42	0.240275D+03	0.286500D+03	0.662660D+01	0.222393D+01
43	0.245080D+03	0.292230D+03	0.679047D+01	0.223990D+01
44	0.249886D+03	0.297960D+03	0.695550D+01	0.225560D+01

45	0.254691D+03	0.303690D+03	0.712169D+01	0.227106D+01
46	0.259497D+03	0.309420D+03	0.728903D+01	0.228628D+01
47	0.264302D+03	0.315150D+03	0.745751D+01	0.230127D+01
48	0.269108D+03	0.320880D+03	0.762713D+01	0.231603D+01
49	0.273913D+03	0.326610D+03	0.779788D+01	0.233057D+01
50	0.278719D+03	0.332340D+03	0.796975D+01	0.234490D+01
51	0.283524D+03	0.338070D+03	0.814274D+01	0.235902D+01
52	0.288330D+03	0.343800D+03	0.831684D+01	0.237295D+01
53	0.293135D+03	0.349530D+03	0.849205D+01	0.238667D+01
54	0.297941D+03	0.355260D+03	0.866835D+01	0.240021D+01
55	0.302746D+03	0.360990D+03	0.884575D+01	0.241357D+01
56	0.307552D+03	0.366720D+03	0.902424D+01	0.242675D+01
57	0.312357D+03	0.372450D+03	0.920381D+01	0.243975D+01
58	0.317163D+03	0.378180D+03	0.938445D+01	0.245258D+01
59	0.321968D+03	0.383910D+03	0.956616D+01	0.246525D+01

CALCULATION AND COMPARISON OF MAXIMUM SPOTTING
DISTANCES IN VERTICAL COLUMN AND TILTED FIRES

DEFINITIONS AND CONDITIONS USED FOR CALCULATIONS

SPECIFIC GRAVITY OF FIREBRANDS, M = .3000E+03
DRAG COEFFICIENT OF FIREBRANDS IN M = .1200E+01
AVERAGE HEIGHT OF TREE-LINE H IN M = .1524E+02
WIND-SPEED AT TREE HEIGHT UH IN M/S = .8888E+01
FLAME HEIGHT ZF IN M = .2865E+02
RATIO OF BASE OF FLAME HEIGHT TO FLAME HEIGHT = .2000E+00
THE ANGLE OF INCLINATION THETA IN DEG = 33.00
PARTICLE DIAMETER TO FLAME HEIGHT RATIO = .2000E-05
XRATIO -- VERTICAL/TILTED MAXIMUM SPOTTING DISTANCES

--SPOTTING DISTANCE IN M--

	WIND-AIDED	STILL-AIR	XRATIO	BETA
1	0.540159D+03	0.359839D+03	0.666172D+00	0.109485D+01
2	0.586088D+03	0.399335D+03	0.681356D+00	0.114842D+01
3	0.630678D+03	0.438052D+03	0.694573D+00	0.119870D+01
4	0.674061D+03	0.476044D+03	0.706233D+00	0.124612D+01
5	0.716350D+03	0.513363D+03	0.716636D+00	0.129101D+01
6	0.757639D+03	0.550051D+03	0.726007D+00	0.133368D+01
7	0.798010D+03	0.586150D+03	0.734515D+00	0.137436D+01
8	0.837531D+03	0.621694D+03	0.742294D+00	0.141323D+01
9	0.876266D+03	0.656717D+03	0.749450D+00	0.145048D+01
10	0.914267D+03	0.691248D+03	0.756068D+00	0.148624D+01
11	0.951584D+03	0.725313D+03	0.762216D+00	0.152063D+01
12	0.988258D+03	0.758936D+03	0.767953D+00	0.155377D+01
13	0.102433D+04	0.792139D+03	0.773326D+00	0.158575D+01
14	0.105983D+04	0.824944D+03	0.778374D+00	0.161666D+01
15	0.109479D+04	0.857367D+03	0.783133D+00	0.164656D+01
16	0.112924D+04	0.889426D+03	0.787630D+00	0.167554D+01
17	0.116321D+04	0.921138D+03	0.791891D+00	0.170363D+01
18	0.119672D+04	0.952516D+03	0.795938D+00	0.173091D+01
19	0.122979D+04	0.983574D+03	0.799790D+00	0.175742D+01
20	0.126244D+04	0.101433D+04	0.803463D+00	0.178321D+01
21	0.129469D+04	0.104478D+04	0.806972D+00	0.180831D+01
22	0.132656D+04	0.107495D+04	0.810329D+00	0.183276D+01
23	0.135806D+04	0.110485D+04	0.813547D+00	0.185660D+01
24	0.138921D+04	0.113448D+04	0.816636D+00	0.187985D+01
25	0.142002D+04	0.116386D+04	0.819604D+00	0.190255D+01
26	0.145051D+04	0.119299D+04	0.822461D+00	0.192473D+01
27	0.148068D+04	0.122188D+04	0.825213D+00	0.194641D+01
28	0.151055D+04	0.125054D+04	0.827867D+00	0.196760D+01
29	0.154013D+04	0.127897D+04	0.830430D+00	0.198834D+01
30	0.156943D+04	0.130719D+04	0.832907D+00	0.200864D+01
31	0.159845D+04	0.133519D+04	0.835304D+00	0.202853D+01
32	0.162721D+04	0.136299D+04	0.837624D+00	0.204801D+01
33	0.165572D+04	0.139060D+04	0.839873D+00	0.206711D+01
34	0.168398D+04	0.141800D+04	0.842053D+00	0.208583D+01

35	0.171200D+04	0.144522D+04	0.844170D+00	0.210421D+01
36	0.173979D+04	0.147226D+04	0.846226D+00	0.212224D+01
37	0.176736D+04	0.149911D+04	0.848224D+00	0.213994D+01
38	0.179470D+04	0.152580D+04	0.850167D+00	0.215733D+01
39	0.182184D+04	0.155231D+04	0.852058D+00	0.217441D+01
40	0.184876D+04	0.157866D+04	0.853900D+00	0.219120D+01
41	0.187549D+04	0.160484D+04	0.855694D+00	0.220770D+01
42	0.190202D+04	0.163087D+04	0.857443D+00	0.222393D+01
43	0.192835D+04	0.165674D+04	0.859149D+00	0.223990D+01
44	0.195451D+04	0.168246D+04	0.860813D+00	0.225560D+01
45	0.198048D+04	0.170804D+04	0.862438D+00	0.227106D+01
46	0.200627D+04	0.173347D+04	0.864026D+00	0.228628D+01
47	0.203189D+04	0.175876D+04	0.865577D+00	0.230127D+01
48	0.205735D+04	0.178391D+04	0.867093D+00	0.231603D+01
49	0.208264D+04	0.180893D+04	0.868576D+00	0.233057D+01
50	0.210776D+04	0.183381D+04	0.870027D+00	0.234490D+01
51	0.213273D+04	0.185856D+04	0.871447D+00	0.235902D+01
52	0.215755D+04	0.188319D+04	0.872837D+00	0.237295D+01
53	0.218222D+04	0.190769D+04	0.874199D+00	0.238667D+01
54	0.220674D+04	0.193207D+04	0.875533D+00	0.240021D+01
55	0.223112D+04	0.195633D+04	0.876841D+00	0.241357D+01
56	0.225535D+04	0.198047D+04	0.878123D+00	0.242675D+01
57	0.227945D+04	0.200450D+04	0.879380D+00	0.243975D+01
58	0.230341D+04	0.202841D+04	0.880613D+00	0.245258D+01
59	0.232724D+04	0.205222D+04	0.881824D+00	0.246525D+01

TZO -- FINAL LOFTING HEIGHT IN A TILTED COLUMN FIRE
****FOR TZO, SEE FIGURE 2****
ZO -- FINAL LOFTING HEIGHT IN A VERTICAL COLUMN FIRE
****ZO PRESENTED ONLY FOR COMPARISON****
TTT -- TOTAL TIME OF TRAVEL (DIMENSIONLESS) = DTF + DTT + DT
BETA-- PARAMETER IN THE FIRE BRAND TRAJECTORY
EQUATION FOR TILTED FLAMES
(SEE REPORT EQUATION 39)

	TZO	ZO	TTT	BETA
1	0.432495D+02	0.515700D+02	0.102627D+01	0.109485D+01
2	0.480550D+02	0.573000D+02	0.113344D+01	0.114842D+01
3	0.528605D+02	0.630300D+02	0.124230D+01	0.119870D+01
4	0.576660D+02	0.687600D+02	0.135284D+01	0.124612D+01
5	0.624715D+02	0.744900D+02	0.146502D+01	0.129101D+01
6	0.672770D+02	0.802200D+02	0.157884D+01	0.133368D+01
7	0.720825D+02	0.859500D+02	0.169425D+01	0.137436D+01
8	0.768880D+02	0.916800D+02	0.181126D+01	0.141323D+01
9	0.816935D+02	0.974100D+02	0.192983D+01	0.145048D+01
10	0.864989D+02	0.103140D+03	0.204994D+01	0.148624D+01
11	0.913044D+02	0.108870D+03	0.217159D+01	0.152063D+01
12	0.961099D+02	0.114600D+03	0.229475D+01	0.155377D+01
13	0.100915D+03	0.120330D+03	0.241941D+01	0.158575D+01
14	0.105721D+03	0.126060D+03	0.254554D+01	0.161666D+01
15	0.110526D+03	0.131790D+03	0.267315D+01	0.164656D+01
16	0.115332D+03	0.137520D+03	0.280220D+01	0.167554D+01
17	0.120137D+03	0.143250D+03	0.293269D+01	0.170363D+01
18	0.124943D+03	0.148980D+03	0.306459D+01	0.173091D+01
19	0.129748D+03	0.154710D+03	0.319791D+01	0.175742D+01
20	0.134554D+03	0.160440D+03	0.333262D+01	0.178321D+01
21	0.139359D+03	0.166170D+03	0.346872D+01	0.180831D+01
22	0.144165D+03	0.171900D+03	0.360618D+01	0.183276D+01
23	0.148970D+03	0.177630D+03	0.374500D+01	0.185660D+01
24	0.153776D+03	0.183360D+03	0.388516D+01	0.187985D+01
25	0.158581D+03	0.189090D+03	0.402666D+01	0.190255D+01
26	0.163387D+03	0.194820D+03	0.416949D+01	0.192473D+01
27	0.168192D+03	0.200550D+03	0.431362D+01	0.194641D+01
28	0.172998D+03	0.206280D+03	0.445906D+01	0.196760D+01
29	0.177803D+03	0.212010D+03	0.460579D+01	0.198834D+01
30	0.182609D+03	0.217740D+03	0.475380D+01	0.200864D+01
31	0.187414D+03	0.223470D+03	0.490309D+01	0.202853D+01
32	0.192220D+03	0.229200D+03	0.505363D+01	0.204801D+01
33	0.197025D+03	0.234930D+03	0.520543D+01	0.206711D+01
34	0.201831D+03	0.240660D+03	0.535848D+01	0.208583D+01
35	0.206636D+03	0.246390D+03	0.551275D+01	0.210421D+01
36	0.211442D+03	0.252120D+03	0.566826D+01	0.212224D+01
37	0.216247D+03	0.257850D+03	0.582498D+01	0.213994D+01
38	0.221053D+03	0.263580D+03	0.598292D+01	0.215733D+01
39	0.225858D+03	0.269310D+03	0.614206D+01	0.217441D+01
40	0.230664D+03	0.275040D+03	0.630239D+01	0.219120D+01
41	0.235469D+03	0.280770D+03	0.646390D+01	0.220770D+01
42	0.240275D+03	0.286500D+03	0.662660D+01	0.222393D+01
43	0.245080D+03	0.292230D+03	0.679047D+01	0.223990D+01
44	0.249886D+03	0.297960D+03	0.695550D+01	0.225560D+01

45	0.254691D+03	0.303690D+03	0.712169D+01	0.227106D+01
46	0.259497D+03	0.309420D+03	0.728903D+01	0.228628D+01
47	0.264302D+03	0.315150D+03	0.745751D+01	0.230127D+01
48	0.269108D+03	0.320880D+03	0.762713D+01	0.231603D+01
49	0.273913D+03	0.326610D+03	0.779788D+01	0.233057D+01
50	0.278719D+03	0.332340D+03	0.796975D+01	0.234490D+01
51	0.283524D+03	0.338070D+03	0.814274D+01	0.235902D+01
52	0.288330D+03	0.343800D+03	0.831684D+01	0.237295D+01
53	0.293135D+03	0.349530D+03	0.849205D+01	0.238667D+01
54	0.297941D+03	0.355260D+03	0.866835D+01	0.240021D+01
55	0.302746D+03	0.360990D+03	0.884575D+01	0.241357D+01
56	0.307552D+03	0.366720D+03	0.902424D+01	0.242675D+01
57	0.312357D+03	0.372450D+03	0.920381D+01	0.243975D+01
58	0.317163D+03	0.378180D+03	0.938445D+01	0.245258D+01
59	0.321968D+03	0.383910D+03	0.956616D+01	0.246525D+01